Chapter 26
Diesel Engine Performance and Emission Under Hydrogen Supplement

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Abstract This experimental study reports the behavior of diesel engine while being supported by hydrogen supplement. Hydrogen supplement is added through the air intake manifold at the atmosphere condition (0 °C and 101.325 kPa). The study reports the hydrogen supplement effect on the combustion characteristics, engine performance, emission and fuel consumption. The hydrogen supplement is varied by increment of 2 LPM while keeping the engine under fixed output power condition (torque of 14.7 N-m and speed of 1,100 rpm). In order to keep the engine output power fixed, the diesel fuel consumption is reduced and the hydrogen fuel consumption e hydrogen flow rate. For same power condition (torque and speed), the study shows that hydrogen can be used to reduce diesel fuel consumption however this comes on the expense of increasing of NOx emission. The main finding of this study is that compression engine with hydrogen supplement and diesel as the primary fuel starts knocking when hydrogen form 34 % the output power contribution (or 19 % as mass ratio between hydrogen to diesel).

Keywords Hydrogen combustion · Diesel engine · Dual engine

26.1 Introduction

The need for new source of energy has forced scientists and engineers to explore the use of alternative possible fuel to run compression ignition engine such as LGP [1], in order to replace diesel or at least reduce the use of diesel fuel. Two of many factors that affect the use of compression ignition engine are fuel ignition temperature and engine emission has led the authors to explore the use of hydrogen as

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supplement source of energy in compression ignition engine. Hydrogen is one of the most promising alternative fuels that can play great role in replacing fossil fuels. The clean burning characteristics and better performance of hydrogen fuel has led many researchers to investigate the use of hydrogen as a fuel [2]. However, the use of hydrogen as a fuel in spark ignition (SI) engine [3] has showed a significant reduction in power output. In addition at high load, pre ignition, backfire and knocking problems has been reported, hence these problems have limited the use of hydrogen in SI engine [4, 5].

On the other hand, the use of hydrogen has showed a significant increase in efficiency (around 20 %) in compression ignition engine [6] when compared to pure diesel combustion and an increase of 13 % in NOx emission. As reported in literature [7], hydrogen fuel cannot be used as a sole fuel in a compression ignition (CI) engine, since the compression temperature is not enough to initiate the combustion due to its high self-ignition temperature. Therefore, hydrogen is used as dual fuel and combusted with the presence of diesel as the main fuel. In a dual fuel engine the main fuel is either carbureted or injected into the air intake stream with combustion initiated by diesel. The major energy is obtained from diesel while the rest of the energy is supplied by hydrogen. Masood et al. [8] reported a brake thermal efficiency of 30 % when hydrogen is used in the dual fuel mode with diesel at a compression ratio of 24.5. Lee et al. [9] studied the performance of dual hydrogen-diesel fuel engine by using solenoid in-cylinder injection and external fuel injection technique. Lee et al. has reported an increase in thermal efficiency of 22 % for dual injection at low loads and 5 % at high loads compared to direct injection. Lee et al. [10] indicated that in dual injection, the stability and maximum power is accomplished by direct injection of hydrogen. Das et al. [11] have carried out experiments on continuous carburation, continuous manifold injection, timed manifold injection and low pressure direct cylinder injection. Das et al. reported that the maximum brake thermal efficiency of 31.3 % is obtained at 2,200 rpm with 13 N-m torque.

The use of hydrogen fuel is a potential method to reduce the demand on liquid diesel fuel however it comes with the expense of increasing NOx emission. Therefore, the need for techniques to reduce NOx become more vital for dual hydrogen-diesel engine operation. One way to achieve the NOx reduction in diesel engine is by injecting steam to the combustion [12]. Another way of reducing NOx is to operate the hydrogen engine with lean mixtures. Lean mixture results in lower temperature that would slow the chemical reaction, which weakens the kinetics of NOx formation [13, 14].

One of the main feature of hydrogen-operated engine is that it does not produce major pollutants such as hydrocarbon (HC), carbon monoxide (CO), sulphur dioxide (SO_2), smoke, particulate matter, lead, and other carcinogenic compounds. This is due to the absence of carbon and sulphur in hydrogen. However hydrogen-operated engines main disadvantage is the NOx emissions. The formation of NOx mostly is due to the presence of nitrogen in air [15]. When the combustion temperature is high some portion of nitrogen present in the air reacts with oxygen to form NOx.

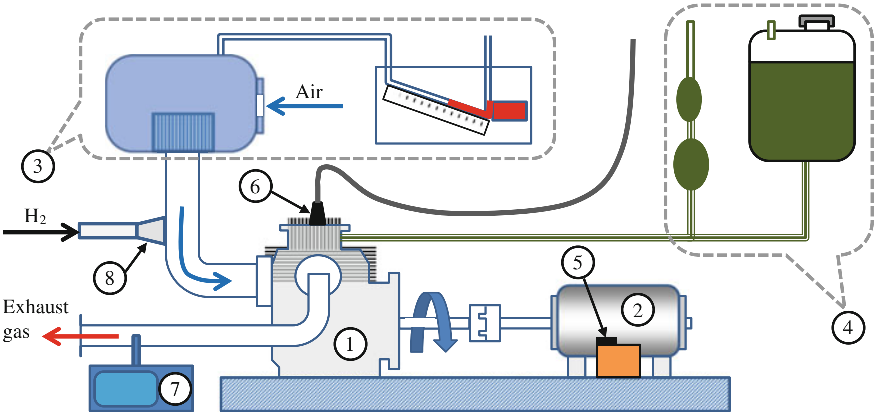

Fig. 26.1 Schematic view of the engine test bed: *1* engine, *2* dynamometer, *3* air intake system with drum tank and inclined manometer, *4* fuel system with fuel tank and flow measuring volume, *5* strain gauge load cell sensor for torque measurement, *6* pressure transducer, *7* emission monitoring systems, and *8* Hydrogen inlet to the air intake manifold

In this study and through dual engine configuration, hydrogen is injected to the air intake manifold as a supplemental fuel which is combusted in the presence of diesel as main fuel and thus replacing a portion of the diesel fuel demanded to produce engine output power. The primary interest of this study is the effect of hydrogen supplement on the performance of a diesel where hydrogen is supplied through the air intake manifold. The study reports the amount of hydrogen supplement that causes engine knocking.

26.2 Experimental Setup

A schematic diagram of the engine with instrumentations is show in Fig. 26.1. The test engine used is a single cylinder DI diesel engine, having a rated power of 5 kW that runs at a constant speed of 3,600 rpm which is modified to work with hydrogen in the dual fuel mode where hydrogen is injected into the air intake manifold as shown in Fig. 26.2.

The engine used in this study is Petter AC1 by Gussons type P8163 which is a four stroke compression ignition air-cooled engine. The engine size is 304 cc with 762 mm pore diameter and 66.7 mm stroke length. The engine has compression ratio of 17, a maximum power of 5 kW at 3,600 rpm and a maximum torque of 15.6 N-m at 2,650 rpm.

As shown in Figs. 26.1 and 26.2, hydrogen gas is injected into the air intake manifold at low pressure. A pressure regulator as well as a volumetric rotameter are used to control the hydrogen flow rate. The flow rate of air is measured using a calibrated orifice air-drum manometer arraignment. The diesel flow rate is

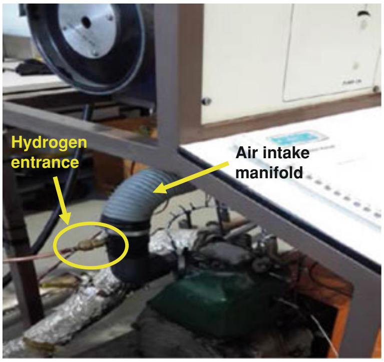

Fig. 26.2 The hydrogen inlet to the air intake manifold

measured by recording required time to consume fixed volume of diesel. The torque of the engine is measured through force transducer that is connected to the electrical dynamometer. The force transducer is calibrated before testing using fixed weight load. The electrical dynamometer is used to load the engine.

The main objective of this experiment is to determine the maximum hydrogen flow rate that diesel engine can handle before reaching knocking and to characterize the engine performance, characteristics, emission and fuel consumption under different flow rate of hydrogen. For this hydrogen is varied from 0 to 8 l per minute insteps of 2 l per minute for the entire load conditions. The emission is measured using RARIO plus SE emission monitoring systems.

26.3 Mathematical Analysis

The engine efficiency and specific fuel consumption is calculated using Eqs. (26.1) and (26.2) respectively:

$$\eta = \frac{W_{out}}{Q_{in}} = \frac{T \cdot \omega}{(\dot{m} \times LHV)_{Diesel} + (\dot{m} \times LHV)_{H_2}} \tag{26.1}$$

$$sfc = \frac{\dot{m}_{fuel}}{W_{out}}. \tag{26.2}$$

The specific fuel consumption is calculated based on diesel fuel consumption, hydrogen fuel consumption and total (hydrogen and diesel) fuel consumption. The lower heating value is used in the calculation since no vapor is condensed during the experiment. The density of hydrogen is calculated at atmosphere pressure and room temperature.

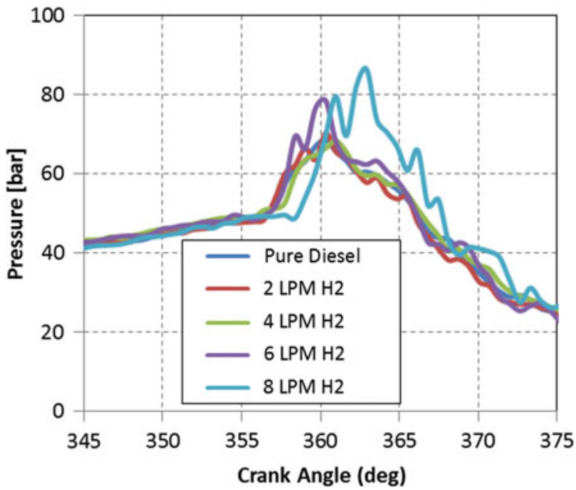

Fig. 26.3 Variation of cylinder pressure with crank angle at 14.7 N-m engine torque and 1,100 rpm engine speed for different amount of hydrogen supplement

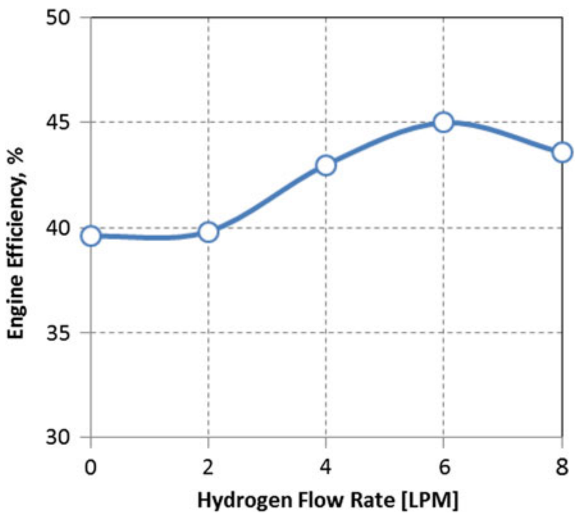

Fig. 26.4 Variation of engine efficiency versus different amount of hydrogen supplement while fixing engine torque at 14.7 N-m and engine speed at 1,100 rpm

26.4 Results and Discussion

The effect of hydrogen supplement on diesel engine performance are shown in Figs. 26.3, 26.4, 26.5, 26.6 and 26.7 for one output power condition with torques of 14.7 N-m and engine speed of 1,100 rpm. The output power condition is 1.69 kW while maximum engine load is 5 kW at 2,650 rpm. During the experiment, as the amount of hydrogen flow rate is increased, the amount of diesel flow rate is decreased to maintain fixed power condition (torque of 14.7 N-m and speed of 1,100 rpm).

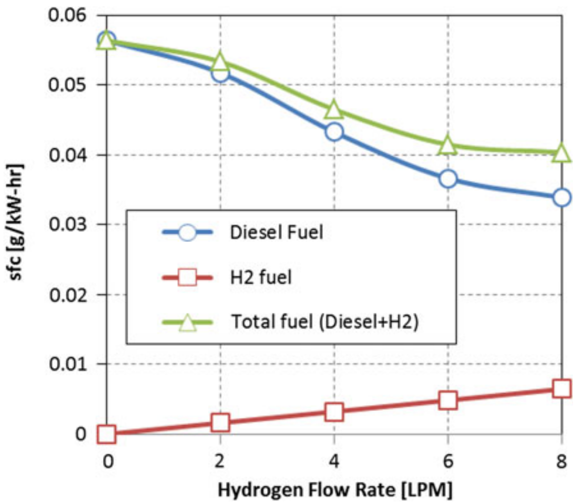

Fig. 26.5 Variation of specific fuel consumption for different amount of hydrogen supplement while fixing engine torque at 14.7 N-m and engine speed at 1,100 rpm

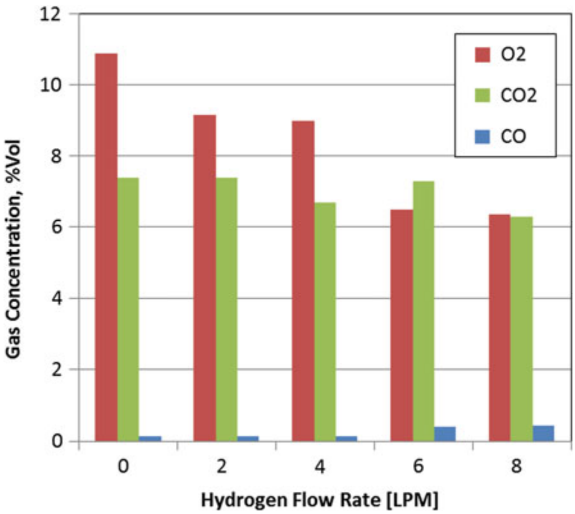

Fig. 26.6 Variation of O_2, CO_2 and CO with different amount of hydrogen supplement, at 14.7 N-m engine torque and 1,100 rpm engine speed

Figure 26.3 shows the cylinder pressure variation with crank angle for different amount of hydrogen supplement flow rates. It is very clear that adding hydrogen will increase the maximum pressure of the cylinder and that pure diesel case has the least peak pressure. It is also clear that adding hydrogen supplement up to 4 LPM (7.5 % weight ratio of hydrogen to diesel) will not have major effect on the pressure rise inside the engine cylinder.

As amount of hydrogen supplement is increasing, Fig. 26.4 shows that engine efficiency is improving from 39.6 % for pure diesel up to 45 % for hydrogen supplement flow rate of 6 LPM. This is expected since hydrogen will burn faster

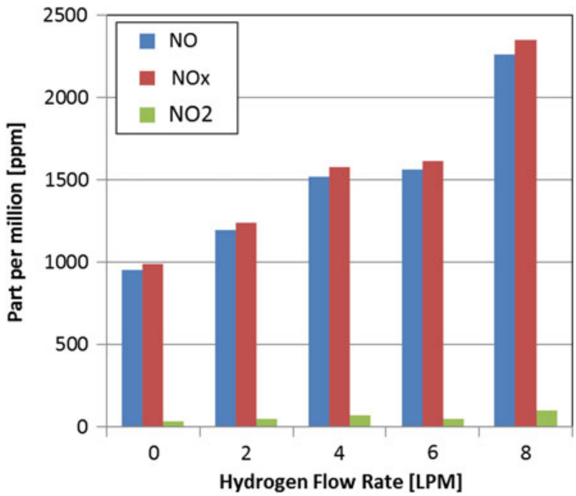

Fig. 26.7 Variation of NO, NOx and NO_2 with different amount of hydrogen supplement, at 14.7 N-m engine torque and 1,100 rpm engine speed

causes higher temperature rise when compared to diesel and hence it boosts engine efficiency. However this trend drops after 6 LPM and engine efficiency drop to 43.6 % at 8 LPM of hydrogen which could be due to lower air flow rate. During the experiment, amount of air introduced to the engine has decreased by a small amount (around 12 % when compared between pure diesel case and 8 LPM hydrogen supplement case). It is expected that this reduction in air flow rate is due to hydrogen who starts occupying more volume of air intake manifold which forced less air inside the engine cylinder.

As expected, introducing hydrogen fuel will reduce the diesel fuel consumption, hence reduce sfc of diesel as shown in Fig. 26.5. The reduction in the diesel specific fuel consumption is more than the increase in the hydrogen specific fuel consumption the LHV of hydrogen is 119.96 MJ/kg while for diesel it is 44.8 MJ/kg. While keeping power output fixed, Fig. 26.5 shows that the total specific fuel consumption decreases as hydrogen supplement is introduced which is due to the enhancement in the engine efficiency and the higher LHV of hydrogen when compared to diesel.

Figures 26.6 and 26.7 show the engine emission and it is clear that as hydrogen supplement increases, the NOx increases and oxygen decreases. This is expected since as more hydrogen is burned higher temperature inside the cylinder is attained which increases engine break thermal efficiency however it increases NOx emission too. It is clear that at 6 LPM of hydrogen supplement, the fraction of reduction in specific fuel consumption when compared to pure diesel is 35 % (=1−(0.036 g/kW h)/(0.056 g/kW h)), while the fraction of increase in NOx emission is 64 % (=(1,615 ppm)/(987 ppm)−1),. Therefore, overall engine performance based on NOx emission has increase by 29 % (=64−35 %).

Knocking has been observed for hydrogen flow rate above 8 LPM ($= 1.1 \times 10^{-5}\,\mathrm{kg/s}$) while diesel consumption is $5.74 \times 10^{-5}\,\mathrm{kg/s}$. In another

words knocking has been observed when hydrogen fraction form a 34 % of total energy supplied by hydrogen-diesel fuel (or 19 % as mass ratio between hydrogen to diesel).

26.5 Conclusions

In this work, an experimental investigation has been conducted to examine the effect of hydrogen supplement on the performance of dual fuel diesel engine. Forgiven engine specification, the data show the following:

- Specific fuel consumption decreases and hydrogen is introduced to the diesel engine due the improvement in engine efficiency and due to the higher LHV of hydrogen when compared to diesel.
- Engine knocking highly occurs when hydrogen flow rate goes beyond 8 LPM (34 % of energy contribution).
- The addition of hydrogen can reduce diesel consumption by 35 % but it will increase NOx emission by more than 64 %.

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References

1. E. Elnajjar, M. Selim, M.O. Hamdan, Experimental study of dual fuel engine performance using variable LPG composition and engine parameters. Energy Convers. Manag. **76**, 32–42 (2013)
2. M. Garni, A simple and reliable approach for the direct injection of hydrogen in internal combustion engines at low and medium pressures. Int. J. Hydrogen Energy **20**, 723–726 (1995)
3. B. Haragopala Rao, K.N. Shrivastava, H.N. Bhakta, Hydrogen for dual fuel engine operation. Int. J. Hydrogen energy **8**, 381–384 (1983)
4. J.B. Heywood, *Internal Combustion Engine Fundamentals*. McGraw-Hill Series in Mechanical Engineering (McGraw-Hill, New York, 1998), p. 508–511
5. J.A. Caton, An investigation of cause of backfire and its control due to creviced volumes in hydrogen fueled engine. Trans. ASME **23**, 204–210 (2001)
6. N. Saravanan, G. Nagarajan, G. Sanjay, C. Dhanasekaran, K.M. Kalaiselvan, Combustion analysis on a DI diesel engine with hydrogen in dual fuel mode. Fuel **87**, 3591–3599 (2008)
7. L.M. Das, Near-term introduction of hydrogen engines for automotive and agricultural application. Int. J. Hydrogen Energy **27**, 479–487 (2002)
8. M. Masood, M.M. Ishrat, A.S. Reddy, Computational combustion and emission analysis of hydrogen-diesel blends with experimental verification. Int. J. Hydrogen Energy **32**, 2539–2547 (2007)
9. J.T. Lee, Y.Y. Kim, C.W. Lee, J.A. Caton, An investigation of a cause of backfire and its control due to crevice volumes in a hydrogen fueled engine. ASME, **123,** 204–210 (2001)

10. T. Lee Jong, Y.Y. Kim, A. Caton Jerald, The development of a dual injection hydrogen fueled engine with high power and high efficiency. 2002 Fall technical conference of ASME-ICED, pp. 2–12, 8–11 Sept 2002
11. L.M. Das, Hydrogen engine: research and development (R&D) programmes in Indian Institute of Technology (IIT) Delhi. Int. J. Hydrogen Energy **27**, 953–965 (2002)
12. A. Parlak, V. Ayhan, Y. Üst, B. Şahin, I. Cesur, B. Boru, G. Kökkülünk, New method to reduce NOx emissions of diesel engines: electronically controlled steam injection system. J. Energy Inst. **85**(3), 135–139(5) (2012)
13. F.J. Michael, H.R. Brunt, The calculation of heat release energy from engine cylinder pressure data. J. Fuels Lubricants **107** (Section 4, SAE 981052, SAE transactions) (1998)
14. J.D. Naber, D.L. Siebers, Hydrogen combustion under diesel engine conditions. Int. J. Hydrogen Energy **23**(5), 363–371 (1998)
15. S.J. Lee, H.S. Yi, E.S. Kim, Combustion characteristics of intake port injection type hydrogen fuelled engine. Int. J. Hydrogen Energy **20**, 317–322 (1995)